Field Demonstration of Novel Architecture Supporting DWDM Data Transmission and Fiber Path Services in Metro/Access-Integrated All-Photonics Network

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Abstract *We propose an extended metro/access integrated network architecture comprising two layers with fiber-based and wavelength-based cross-connects for fiber-path and end-to-end wavelength connection services, respectively. Simultaneous demonstration of 100-Gbit/s dense wavelength-division-multiplexing transmission and field-access fiber sensing without interference confirms its effectiveness.*

Introduction

With the proliferation of new life-styles involving remote work and entertainment in the post-Covid-19 era and the emergence of advanced use cases such as remote surgery, there is increased demand for a wide-bandwidth guarantee and deterministic latency. How to actualize such an infrastructure for communications and data exchange is one concern facing network operators. In conventional networks, optical signals are converted to electrical signals once at the access/metro boundary for aggregation, multiplexing, and switching in the electrical domain. This hierarchical architecture based on statistical multiplexing causes variations in throughput, latency, and jitter depending on the traffic load. Based on this background, one direction of network evolution is to integrate access and metro networks by extending conventional dense wavelength-division-multiplexing (DWDM) from metro to access areas [1,2]. This All-Photonics Metro-Access Converged Network (APN) provides end-to-end wavelength connectivity between any endpoints, *e.g.*, end-user premises, edge cloud, and center cloud, with wavelength cross-connect (WXC) functions, and guarantees wide bandwidth ultimately achieving low latency and jitter. The APN also enables user terminals (UTs) to launch DWDM signals using protocols that are the most suitable for their applications.

Another concern for network operators is to create new values by making use of a widely deployed fiber infrastructure, which increases revenues. Recently, as a non-communication use case, much attention has been focused on monitoring objects around deployed fibers, *e.g.*, vehicle traffic, temperature, and earthquakes, by utilizing fiber sensing technologies [3]. In addition, quantum communication technologies such as quantum key distribution (QKD) for authentication have been actively investigated for use cases that require high confidentiality, *e.g.*, on-line stock transactions and military applications. In general, the peak power of a fiber sensing pulse immediately after being launched from the interrogator is much higher than the average power of the DWDM signals for communications. Moreover, the power of the QKD signal is much lower than that of the DWDM signals. Therefore, the requirements for cross-connect for fiber-sensing light and QKD signals are far more severe than those for DWDM signals. Neither fiber-sensing light nor QKD signals can pass through optical amplifiers typically used in WXCs. These factors make it difficult to use the APN based solely on WXCs for these emerging use cases.

This paper proposes extending the APN architecture so that it comprises a fiber path layer in addition to the existing wavelength connection layer. On the fiber path layer, cross-connects are executed per fiber instead of per wavelength. Next, according to the extended APN architecture, an example configuration of the access node of the APN, defined as Photonic Gateway (GW) [2], is presented, which enables the APN to accommodate new use cases with various optical interface and crosstalk requirements. Using Photonic GW prototypes and field access fibers, the effectiveness of the extended APN architecture is validated through demonstration of simultaneous transmission of 100-Gbit/s DWDM signals on the wavelength connection layer and fiber sensing lights on the fiber path layer without interference.

Extended APN Architecture

Figure 1 shows the proposed APN architecture comprising two layers. The fiber path layer is newly defined under the wavelength connection layer that flexibly provides end-to-end connectivity such as data center interconnects on a wavelength basis. The fiber path layer dynamically provides tunnels for optical signals and lights to travel even across nodes, regardless of the wavelength, so long as the fiber exists. Note that the fiber path layer does not include an optical amplification function.

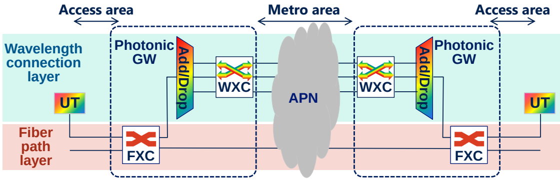

Fig. 1: Proposed extended APN architecture.

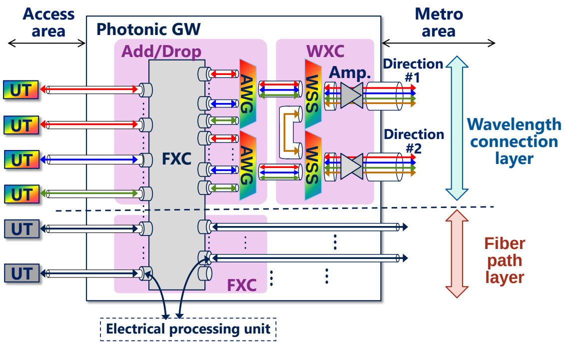

Fig. 2: Example configuration of Photonic GW.

The following two functions are required for the Photonic GW in the extended APN architecture. The first is the function of the fiber path layer to transfer flexibly an incoming optical signal or light to different ports regardless of its wavelength. Modules for fiber-based cross-connects typically have a lower level of crosstalk between connections within the module than that for wavelength-based ones. Therefore, it is expected that this fiber path layer will enable the APN to accommodate light and signals such as fiber sensing light and QKD signals with severe cross-connect requirements. This function also enables the Photonic GW to handle various types of optical paths including non-DWDM for the short reach, *e.g.*, MFH. Short-reach non-DWDM optical paths can be dropped outside the Photonic GW and terminated at the access/metro boundary for some processing in the network or service function layers. The second is the function of the wavelength connection layer, which corresponds to add/drop and WXC functions similar to those of a ROADM.

Figure 2 illustrates an example configuration of a Photonic GW for the extended architecture. This Photonic GW includes fiber cross-connects (FXCs), arrayed waveguide gratings (AWGs), wavelength selective switches (WSSs), and optical amplifiers. The FXC transfers an incoming optical signal or light on a port basis, *i.e.*, functions as a cross-connect on the fiber path layer. On the other hand, the combination of an FXC and AWG certainly works for adding/dropping DWDM signals on the wavelength connection layer for fixed-grid networks. This is a variant of conventional add/drop modules while multicast switch (SW) type and WSS type modules are mainly used in current products [4]. The combination of WSSs and optical amplifiers functions as a WXC on the wavelength connection layer.

The add operation is as follows. After the FXC forwards the optical signals from the access side to an AWG port according to the wavelength of the optical signal, the AWG multiplexes the optical signals and outputs them in the direction that the signals are sent to the neighboring node. The drop operation is as follows. After the AWG demultiplexes DWDM signals and outputs them to different FXC ports, the FXC forwards the optical signals to the access-side ports according to their destinations. That is, the combination of an FXC and AWG is considered to be an integrated function block for cross-connect on the fiber path layer and add/drop on the wavelength connection layer. In this sense, the configuration shown in Fig. 2 is efficient.

Experimental Demonstration

Figure 3 shows the experimental configuration. Two Photonic GW prototypes (Ph-GWs) conforming to the extended APN architecture are connected via a 10-km fiber bobbin and controlled by a single APN controller. Each Ph-GW has one piezo-based optical SW as an FXC, 100-GHz-spaced AWGs, a twin 1×20 WSS, and EDFAs for booster/pre-amplification.

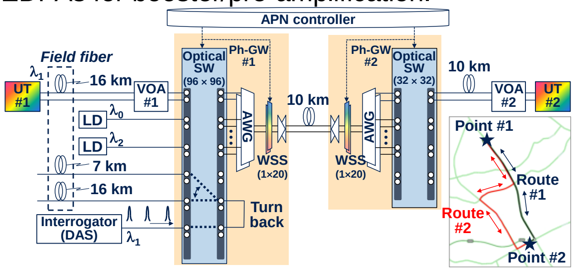

Fig. 3: Experimental configuration.

As a UT for the wavelength connection service, Galileo 1, a coherent transport SW, is used to measure end-to-end DWDM transmission characteristics. It transmits/receives a 100-Gbps DP-QPSK signal with a wavelength of 1550.12 nm (λ_1). A 16-km field fiber is inserted between UT #1 and Ph-GW #1, and a 10-km fiber bobbin is inserted between UT #2 and Ph-GW #2. To evaluate the influence of crosstalk in the Photonic GW, the input power from UT #1 to Ph-GW #1 is varied using variable optical attenuator (VOA) #1. VOA #2 is used for bit-error rate (BER) measurements. As dummy DWDM channels, two continuous wave lights with the wavelengths of 1549.32 nm (λ_0) and 1550.92 nm (λ_2), respectively, are also input to Ph-GW #1. Figure 4(a) shows the spectrum at the Ph-GW #1 output.

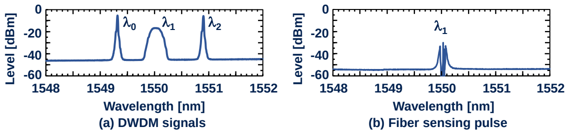

Fig. 4: Optical spectra (Res. = 0.02 nm).

As a service in the fiber path layer, fiber sensing is adopted this time. The pulse from the interrogator is input to Ph-GW #1 from the access side and turned back into a field access fiber. The turn-back function of the Photonic GW, which enables direct optical connection between two UTs under the same Photonic GW, is used [2]. Two access fibers are measured. As shown in the inset to Fig. 3, one fiber is 7-km long from Point #1 to Point #2 along Route #1, while the other is a 16-km fiber in a loop-back configuration from Point #1 to Point #1 along Route #1 and Route #2. As shown in Fig. 4(b), the wavelength of the pulse is set to 1550.12 nm (λ_1), the same as the measured DWDM channel. As the interrogator, distributed acoustic sensing (DAS) equipment, which launches frequency-division-modulated pulses from 50 MHz to 450 MHz in 50-MHz intervals, is used [5]. The width and the repetition frequency of the pulse were 320 ns (40 ns $\times$ 8) and 5 kHz, respectively. Since its average power is fixed at -6.0 dBm at Ph-GW #1 input, the peak power is +22 dBm.

Figure 5(a) shows the BER characteristics of the DWDM signal received at UT #2 when the input power of the DWDM signal to Ph-GW #1 is -20 dBm. Although the peak power of the fiber sensing pulse is 42 dB higher, no BER degradation due to crosstalk is observed. When the DWDM signal power is reduced to -30 dBm, again no BER degradation due to crosstalk is observed. For comparison, Fig. 5(b) shows the BER characteristics when the combination of FXC and AWGs is replaced with an M×N WSS, assuming that the fiber sensing is employed in the network based solely on the WXCs like in [3]. While the OSNR degradation due to the relatively large insertion loss of the WSS degrades the BER values, we also find that the fiber sensing pulse degrades the post-FEC receiver sensitivity by more than 8.3 dB. These results certainly prove that coexistence between conventional DWDM signals and light and signals with stringent cross-connect requirements is achieved with the newly defined fiber path layer.

Figure 6 shows DAS waterfall plots obtained through offline processing of the back-scattered lights from two field fibers captured by the interrogator. These charts show the optical phase transition of the backscattered pulse in response to the strain added to the fibers deployed underground. The single-trip distance from the interrogator and time are represented on the horizontal and vertical axes, respectively. The color indicates the optical phase of the backscattered pulse. Downward and upward transitions along the fiber show how vehicles traversed the route. The difference in slope direction between the two plots successfully shows that two different routes are measured. It can be seen that clear DAS traces of two paths can be obtained even with FXC reflections and losses. Selection of the field fiber under test is performed simply by changing port connection inside the FXC through the APN controller. This Photonic GW configuration enables access and metro fiber sensing, unlike the node configuration in [6] dedicated to metro fiber sensing.

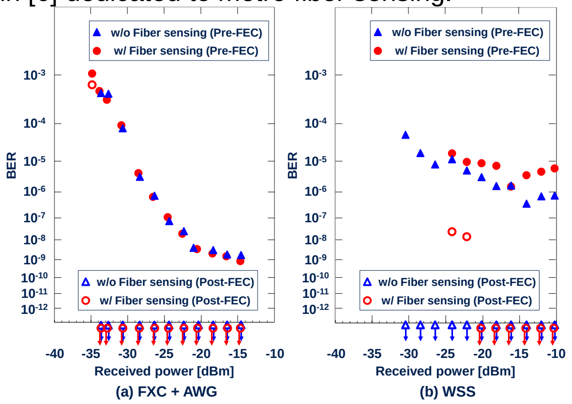

Fig. 5: BER characteristics of 100-Gbit/s DWDM signal.

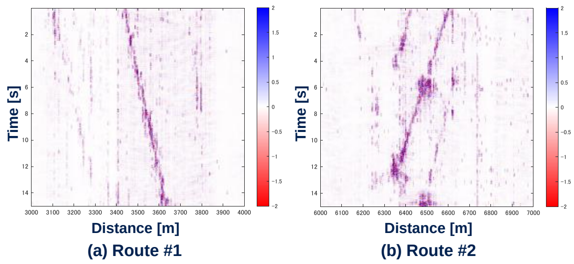

Fig. 6: DAS waterfall plots.

Conclusions

We proposed an extension that adds a fiber path layer to the APN architecture and confirmed its feasibility using a Photonic GW prototype conforming to the architecture. The field demonstration shows that the FXC simultaneously functions as a cross-connect on the newly defined fiber path layer and handles a part of the add/drop operations on the wavelength connection layer without interference even when the difference in the input power level exceeds 52 dB, which simplifies the Photonic GW configuration.

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